eRHIC beam parameters, synchronization, polarization

V. Ptitsyn

Essential design features

- Luminosity advance from HERA by at least factor 20 :
  - Smaller beam size in the IP (allowed for by the linac-ring collision scheme)

- Transverse and longitudinal cooling of the hadron beams (Coherent Electron Cooling)
  - Small angular spread at the IP (the detector requirement for small angle collision products detection)
  - Small bunch length required for the luminosity at low beta* IR

- Crab-crossing scheme to prevent the luminosity reduction due to the 10 mrad crossing angle at the IP

Assumed limits on beam parameters

- Electron polarized current: 50 mA

  Above present state-of-the-art.

- $\beta^* = 5$ cm for all species

- Space charge parameter : 0.035

  From RHIC beam experiments.

- Proton (ion) beam-beam parameter: 0.015

  From RHIC operation experience.

- Bunch frequency: 9.38 MHz

- Hadron bunch length (< 10 cm).

  From Hourglass effect and Crab-crossing.

Proton beam parameters

	eRHIC	Achieved at RHIC
Energy, GeV	100-250	Runs at 31, 100, 250 (255) GeV
Number of bunches	111	111
Bunch intensity, 10^{11}	0.3	1.8 (at store)
Normalized 95% emittance, 1e-6 m	1.6	~15-20 mm*mrad at the store
beta*, cm	5	65
rms bunch length, cm	5	~50 cm
Store polarization	70%	~62% at 100 GeV, ~58% at 250 GeV

eRHIC proton bunch intensity is well below that achieved at RHIC
- Eliminates problems related with the high peak beam current: cold beam pipe heating, BPM cable heating, ...
- No need for the space charge compensation system (at lower proton energies).

Machine cost saving at the acceptable luminosity.

|	e	p	$^2He^3$	$^{79}Au^{197}$
Energy, GeV	10	250	167	100
CM Energy, GeV		100	81.7	63.2
Bunch frequency, MHz	9.4	9.4	9.4	9.4
Bunch intensity (nucleons), 10^{11}	0.33	0.3	0.6	0.6
Bunch charge, nC	5.3	4.8	6.4	3.9
Beam current, mA	50	42	55	33
Hadron rms normalized emittance, 1e-6 m		0.27	0.20	0.20
Electron rms normalized emittance, 1e-6 m		20	22	36
$\beta*$, cm	5	5	5	5
Hadron beam-beam parameter		0.015	0.014	0.008
Space charge parameter		0.006	0.016	0.016
Electron beam disruption		4.3	5.2	1.9
rms bunch length, cm	0.4	5	5	5
Polarization, %	70	70	70	70
Peak e-nucleon luminosity, x 10^{33}, $cm^{-2}s^{-1}$		1.1	2.1	1.3

Possible luminosity enhancement by the electron pinch effect during the collision is not included here (the factor~1.4)
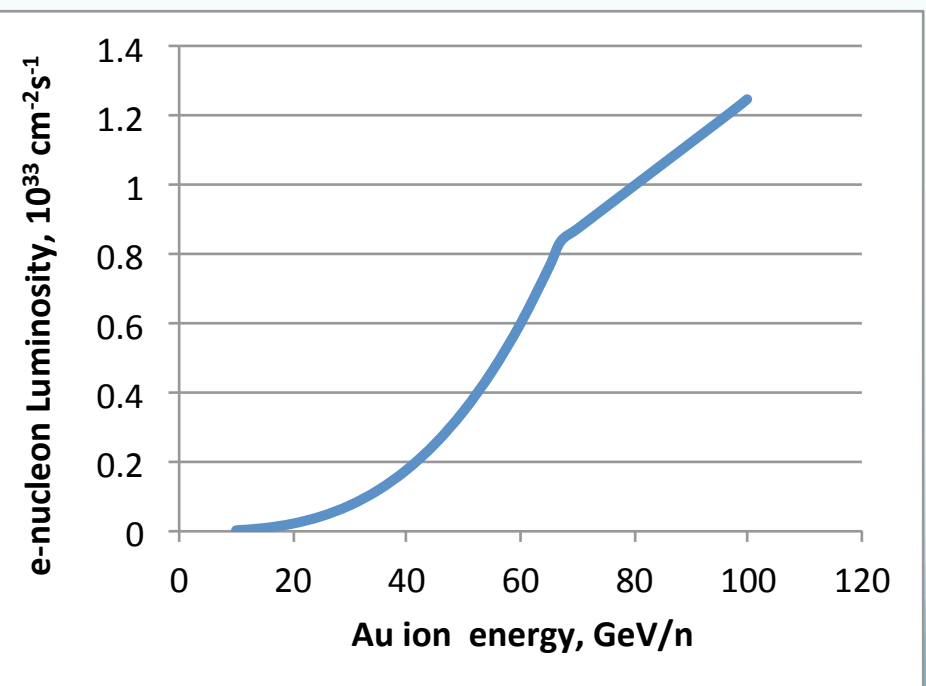
Luminosity energy dependence

$$\Delta Q_{sp} \leq 0.035$$

Defined by the beam-beam limit

Defined by space charge limit, reduced N_p
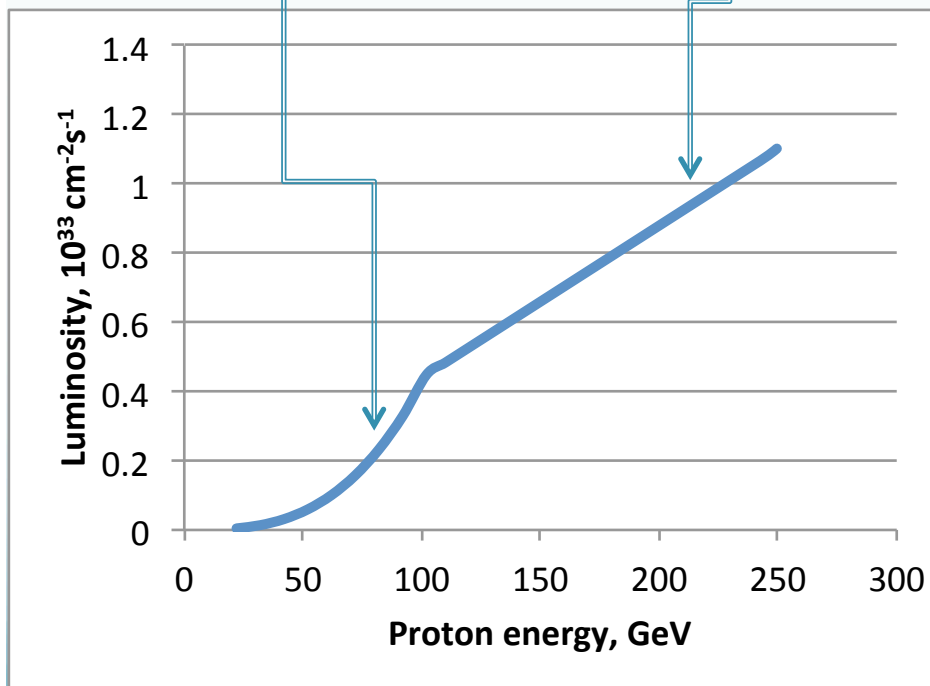

Electron-proton luminosity

Electron-Au nucleon luminosity

Electron-hadron beam synchronization

Main synchronization condition: the electron and hadron bunch frequencies at the collision points have to be the same: $f_{be} = f_{bh}$
But, the hadron bunch frequency (at the fixed circumference) depends on the hadron energy

Hadron revolution frequency at fixed circumference, kHz

Equivalent circumference lengthening, cm
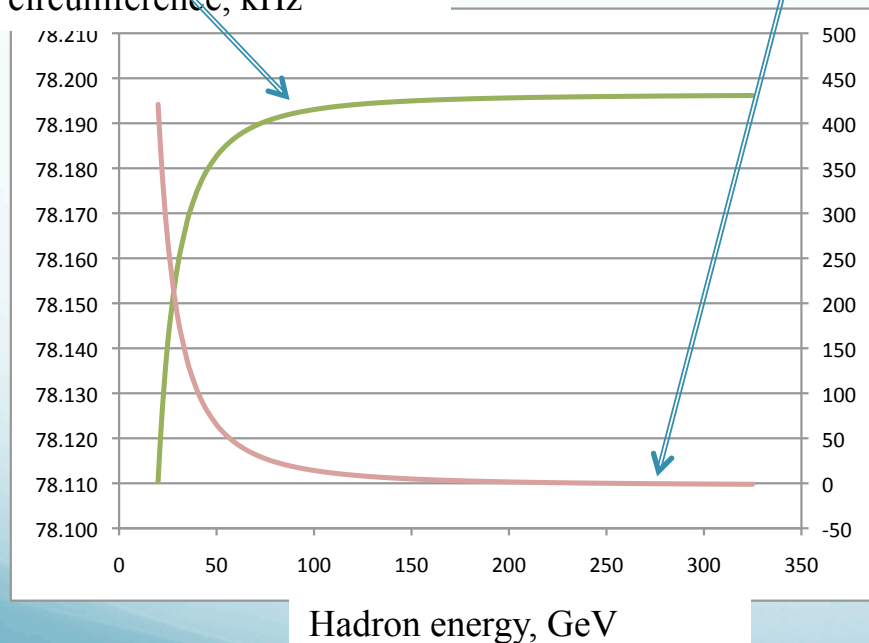
$\Delta C_e(250\ \text{GeV-}50\ \text{GeV}) \sim 65\ \text{cm}$

Electron bunch frequency has to match the hadron bunch frequency in wide energy range: 50-250 GeV/n

Hadron energy, GeV

Synchronization schemes

- **Delay lines for electrons.**
  Initially considered approach.
  - But, the separate delay lines have to be placed in every electron energy recirculating pass. (11 delay lines !)
  - Also, the electron bunch frequency (from the gun) and electron linac RF frequency have to be adjusted with the hadron energy
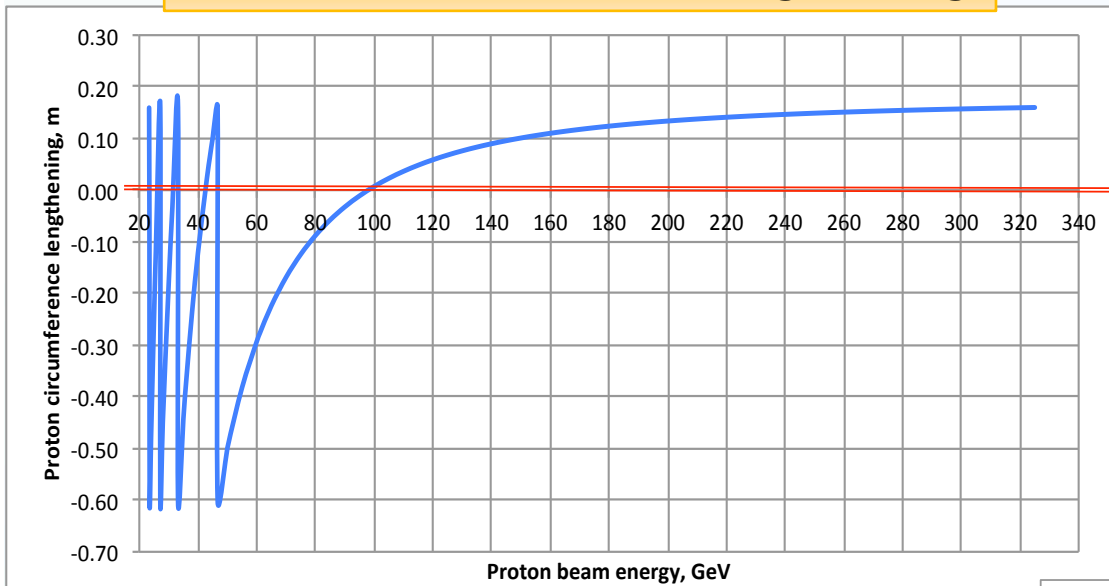
- **Hadron delay line**
  Presently accepted solution.
  - Preliminary design exists with up to 16 cm path lengthening ability.
  - The bunch frequency and the electron linac RF frequency are constant in the proton energy range from 100 to 250 GeV.

- **The harmonic switching** method is assumed to operate with the hadron energies <50 Gev/n

Hadron circumference lengthening and harmonic switching

Hadron circumference lenghtening

$$C_e = \frac{h_e}{5280}\frac{C_h}{\beta_h}$$

Assumes max 16cm delay line (16 cm at 325 GeV)

The operation is possible only above the red line (at positive path lengthening)

Sharp changes corresponds to the electron RF harmonic change

Accessible proton energy ranges:
100-325 GeV; 43-46 GeV; 31.6-33.2 GeV;
26.3-27.1 GeV; 23-23.5 GeV

But, the harmonic switching modifies also the bunch patterns, which may become inappropriate (ions, linac transients)

Linac RF frequency
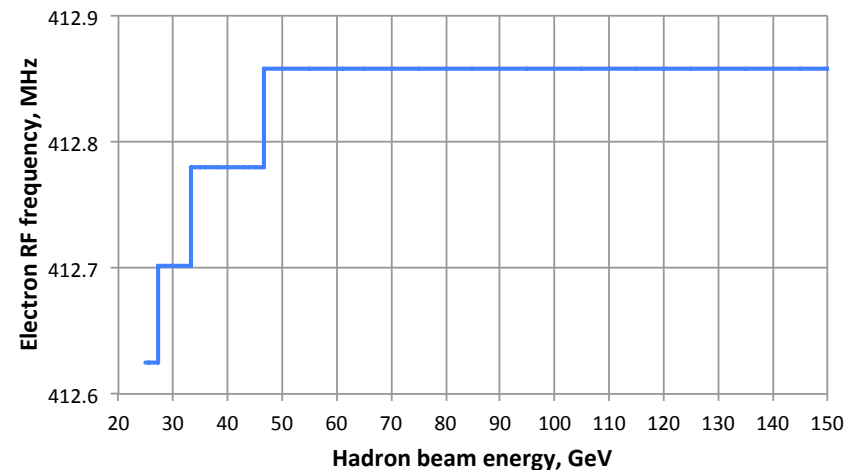
Frequency parameters at different hadron energies

|	Protons		Au ions	
Hadron energy, GeV	250	100	100	50
γ-factor	266.5	106.6	107.4	53.7
β-factor	0.9999930	0.9999560	0.9999566	0.9998265
Hadron revolution frequency, kHz	78.193	78.193	78.193	78.178
Bunch repetition rate, MHz	9.383	9.383	9.383	9.381
Electron bunch to RF harmonic	44	44	44	44
Electron RF frequency, MHz	412.858	412.858	412.858	412.780
Electron RF harmonic	5284	5284	5284	5283
Electron circumference, m	3836.918	3836.918	3836.918	3836.918
Hadron circumference, m	3833.987	3833.845	3833.848	3834.074

Possible alternative to the harmonic switching: sextant line switching

D.Trbojevic's proposal

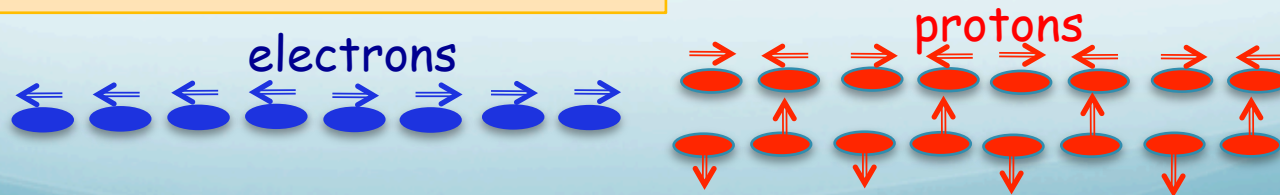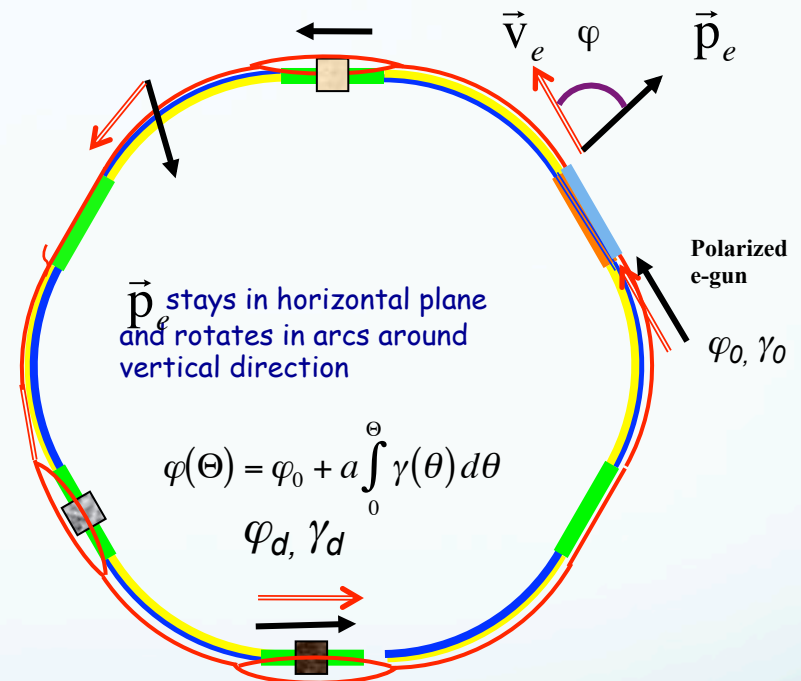Switch the hadron beam trajectory in one sextant between the present Blue and Yellow hadron lines

$\Delta L = 91$ cm

Preserves the beam pattern and the electron RF frequency

Ion Delay Line

Use for 250 GeV

Use to jump to energies below 50 GeV
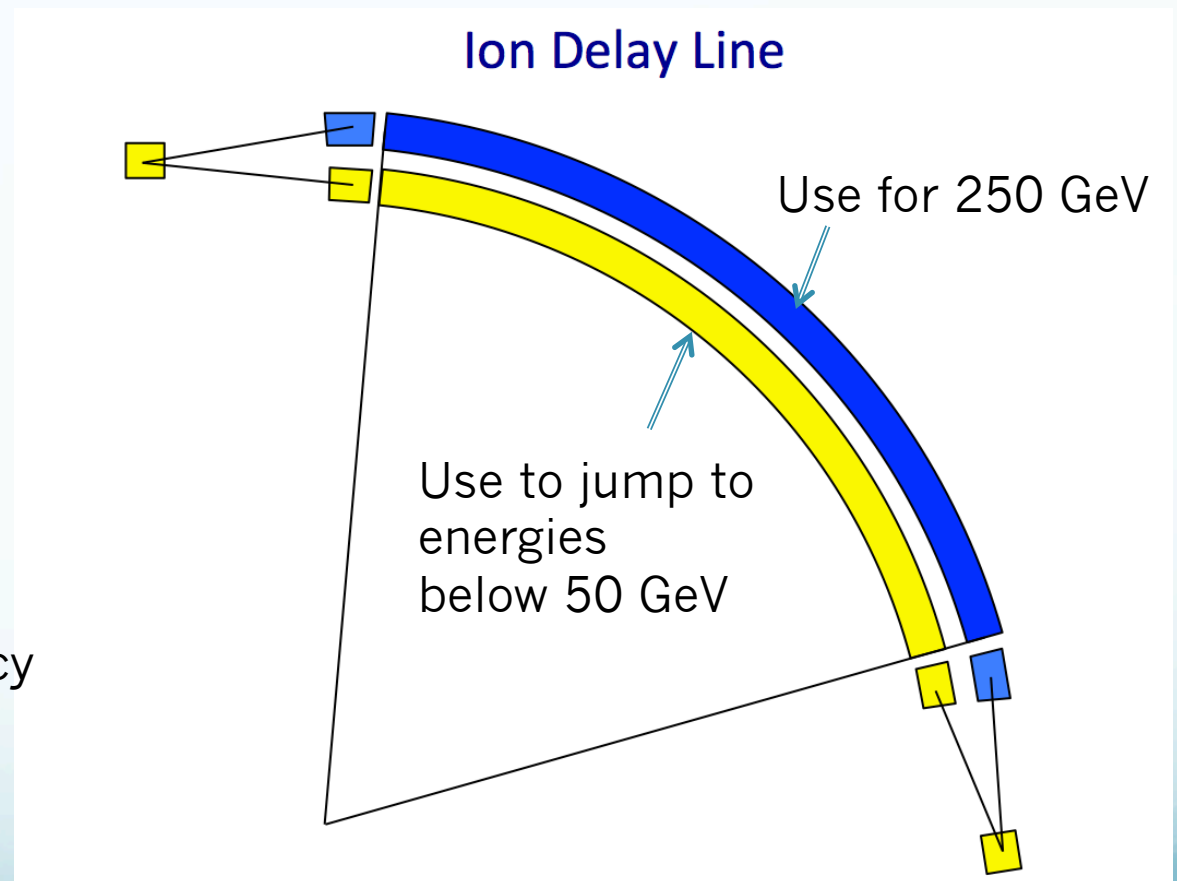
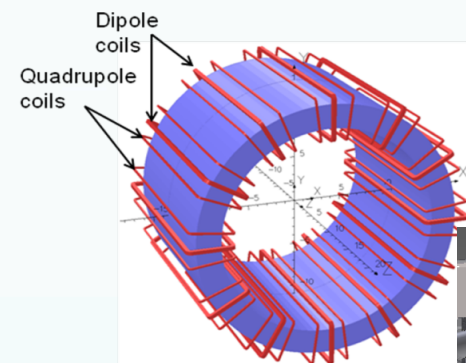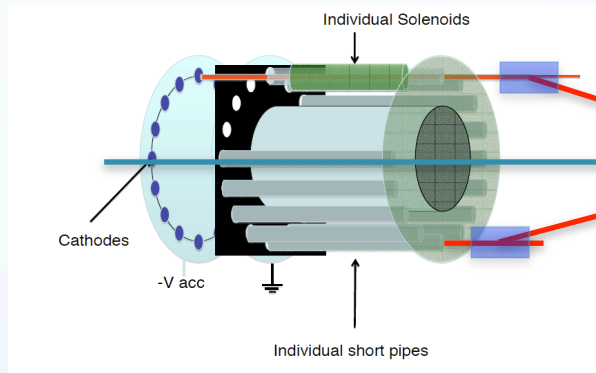# Electron polarization in eRHIC

- High polarized beam current produced by the e-gun: 50 mA

- Direction of polarization can be switched by changing helicity of laser photons in and arbitrary bunch-by-bunch pattern

- Linac accelerator -> No depolarizing resonances!

- The experiments are interested in (only) longitudinal polarization in the collision point(s)
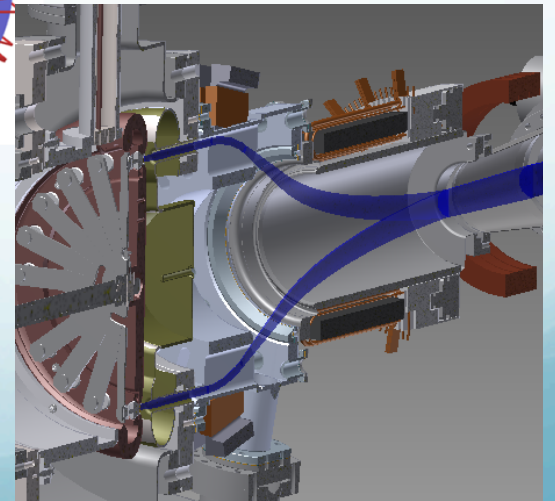
$\vec{v}_e$ φ $\vec{p}_e$

Polarized e-gun

φ_0, γ_0

$\vec{p}_e$ stays in horizontal plane and rotates in arcs around vertical direction

$$\varphi(\Theta) = \varphi_0 + a \int_0^\Theta \gamma(\theta)\, d\theta$$

φ_d, γ_d

electrons

protons

50 mA polarized electron source R&D

BNL Gatling Gun:
the current from multiple cathodes is
merged: 20 cathodes, 2.5 mA each

Individual Solenoids

Cathodes

-V acc

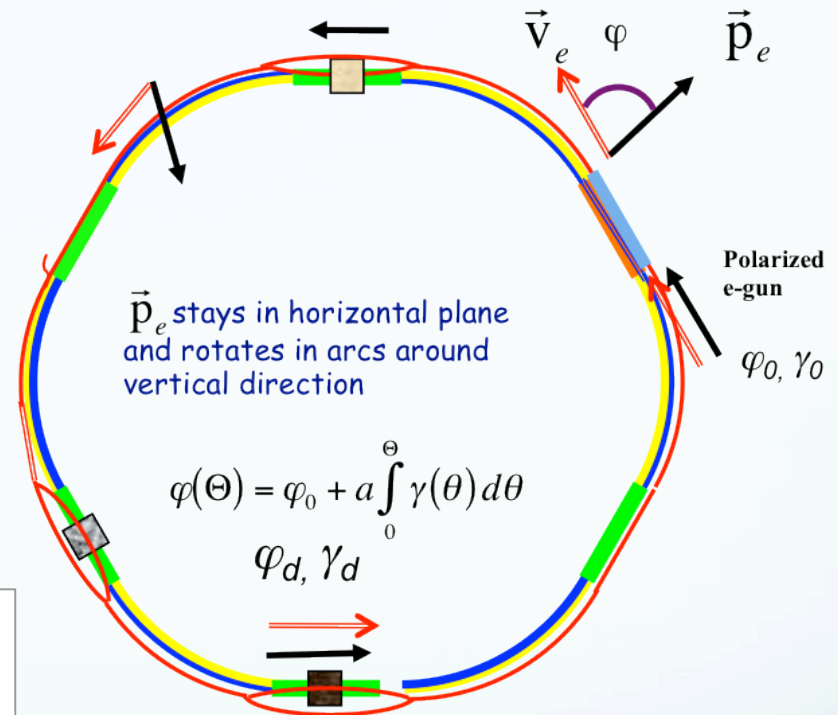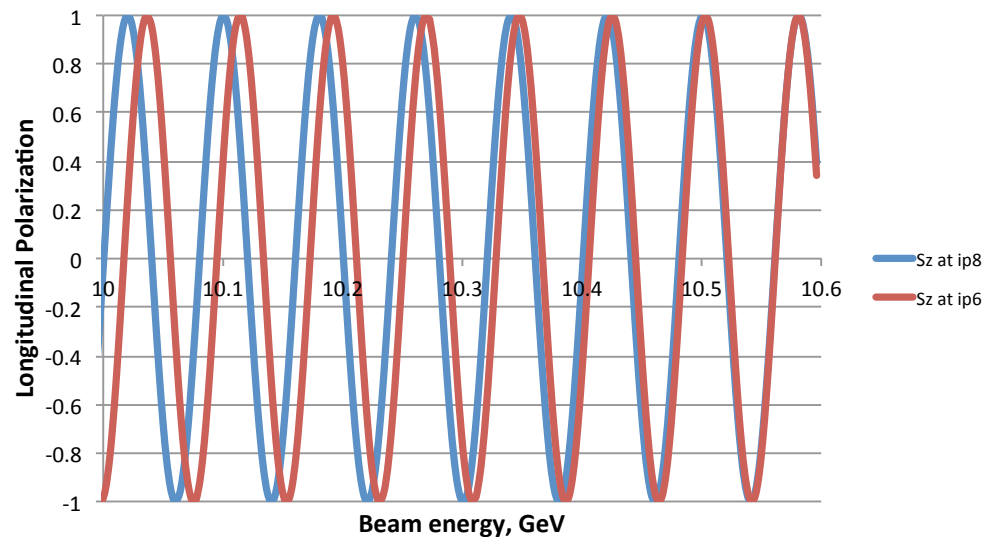Individual short pipes

Dipole coils

Quadrupole coils

▪GG prototype is under construction
▪First gun testing: end of 2014

Longitudinal Polarization at IPs

- eRHIC avoids lengthy spin rotator insertions
  Cost saving
- Beam polarization vector rotates in the
  horizontal plane during the acceleration.
- Longitudinal polarization happens at the IPs
  at particular energies
- Longitudinal polarization in both IP6 and IP8:
  at 9.26 GeV and 10.58 GeV

$\vec{v}_e$ φ $\vec{p}_e$

$\vec{p}_e$ stays in horizontal plane
and rotates in arcs around
vertical direction

Polarized
e-gun

φ_0, γ_0

$$\varphi(\Theta) = \varphi_0 + a \int_0^\Theta \gamma(\theta)d\theta$$

φ_d, γ_d

Beam energy error ~4 10⁻⁴ causes
longitudinal polarization loss ~5%

Tolerance on the linac energy gain:
~2 10⁻⁴
Or a spin rotator (Wien filter) has to be
added to 12 MeV injector

Spin decoherence

$$\frac{d\left(\Delta\varphi_{sp}\right)}{d\theta} = A\Delta E \; ; \qquad A = 2.27\frac{1}{GeV}$$

$$\Delta E = E - E(z = 0)$$

- The energy spread in the beam causes the decoherence and the loss of beam polarization

- The eRHIC beam energy spread is dominated by the effect of the linac accelerator voltage waveform which introduces the quadratic dependence of the spin angle on the longitudinal coordinate of a particle

- Other important effects contributing to the energy spread: the beam interaction with the resistive wall and the cavity wakes, and the longitudinal motion errors (like R_{56} and path length errors)

Polarization at IPs at 10 GeV
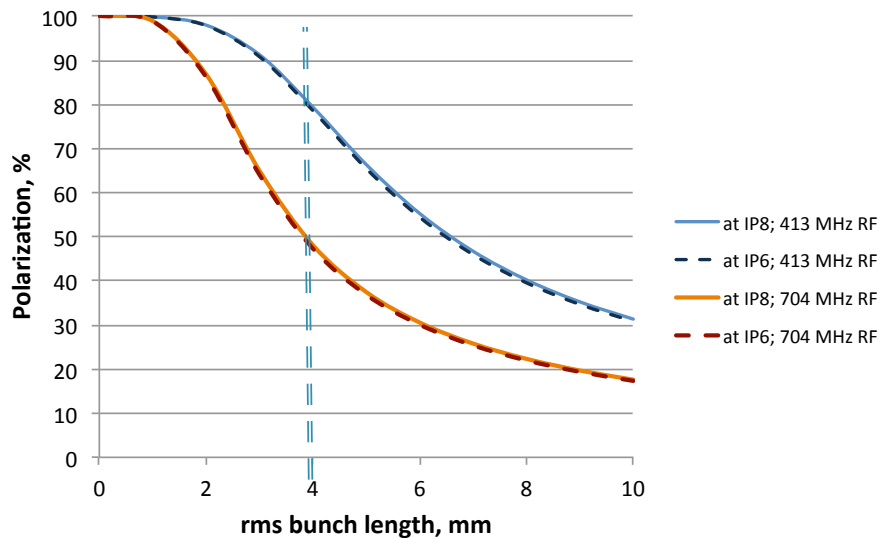
Shown is the averaged polarization: $P = \langle \cos(\Delta\varphi_{sp}) \rangle$ for two RF system choices

Polarization, % (vertical axis), rms bunch length, mm (horizontal axis)

Legend:
— at IP8; 413 MHz RF
- - at IP6; 413 MHz RF
— at IP8; 704 MHz RF
- - at IP6; 704 MHz RF

The rms bunch length is limited to 4 mm or less by the spin decoherence effect.

Longitudinal polarization profile along the bunch (as seen at 10 GeV in IP8)

P_z

Legend:
50 mA current
zero current

Longitudinal coordinate, mm

The energy spread created by the beam interaction with the beam pipe resistive wall and with the linac cavity wakes reduces spin de-coherence effect
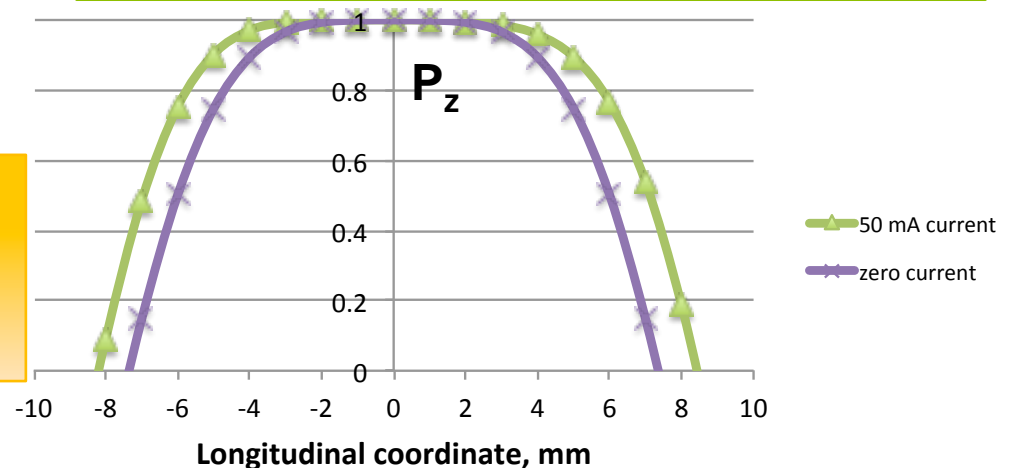
Synchrotron radiation: polarization diffusion

- Well known effect from the electron storage rings:
  Quantum nature of the synchrotron radiation leads to depolarization
- For eRHIC the mechanism is related with the sudden changes of the spin precession frequency.

Diffusion equations for second moments of the energy deviation-spin angle distribution:

$$\overline{\Delta E^2}' = \omega$$

$$\overline{\Delta E \Delta \phi}' = \alpha \overline{\Delta E^2}$$

$$\overline{\Delta \phi^2}' = 2\alpha \overline{\Delta E \Delta \phi}$$

$$\omega = \frac{C}{\rho^3} \lambda_c r_e \gamma_0^5 E_0^2 \qquad C = \frac{110\sqrt{3}}{144}$$

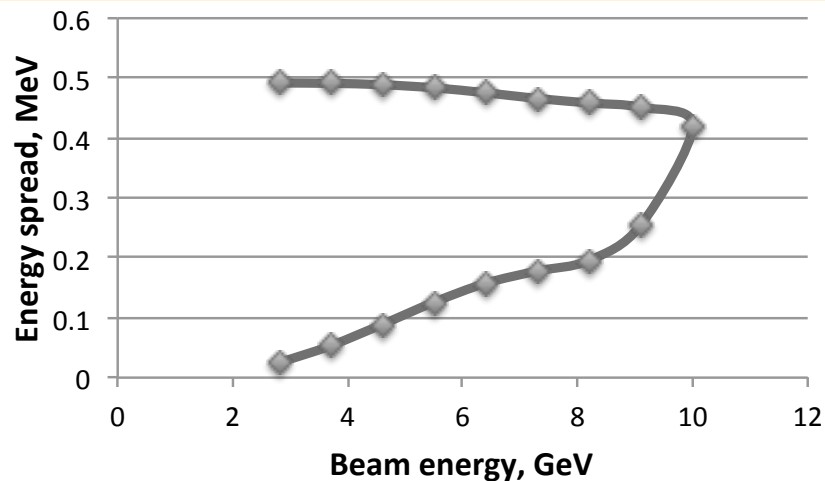$$\alpha = \frac{1}{\rho E_{r1}} \qquad E_{r1} = 0.441\,\text{GeV}$$

Solution of these linear equations can be found as the one cell (or one turn) transformation:

$$V = MV_0 + W \qquad V = \begin{pmatrix} \overline{\Delta E^2} \\ \overline{\Delta E \Delta \phi} \\ \overline{\Delta \phi^2} \end{pmatrix}$$
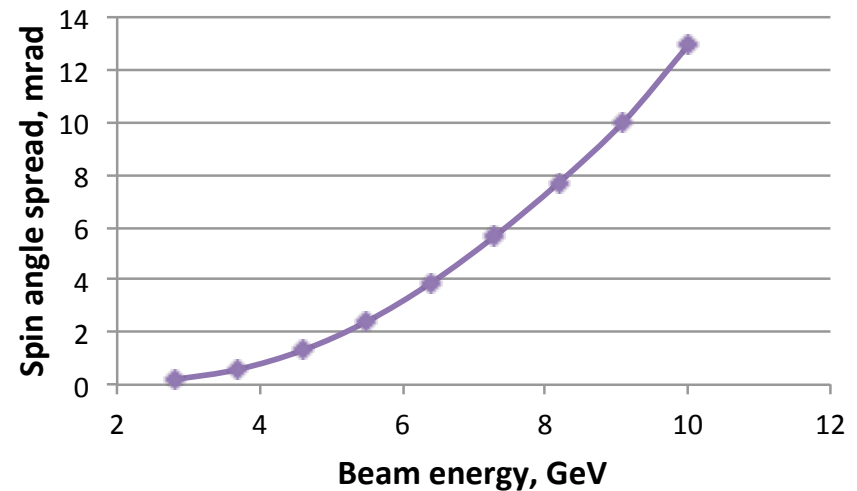
Then the second moments vector can be easily propagated through all recirculating turns

SR depolarization

Accumulated energy spread.
Both the acceleration and the deceleration are shown.

Accumulated spin angle spread.
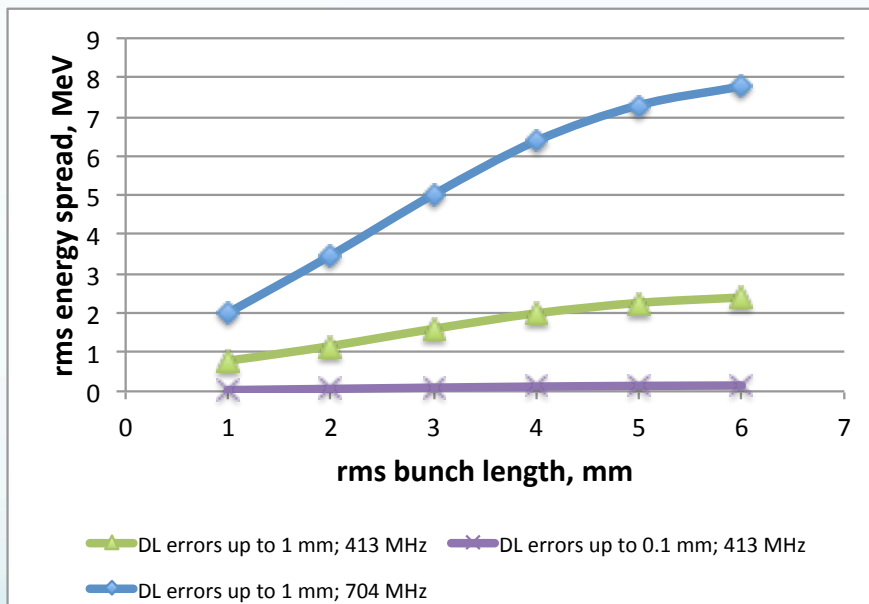Only the acceleration is shown.

The resulting depolarization at 10 GeV is small (<1%)

This data has been used also to verify the simulation results (F.Meot's talk)
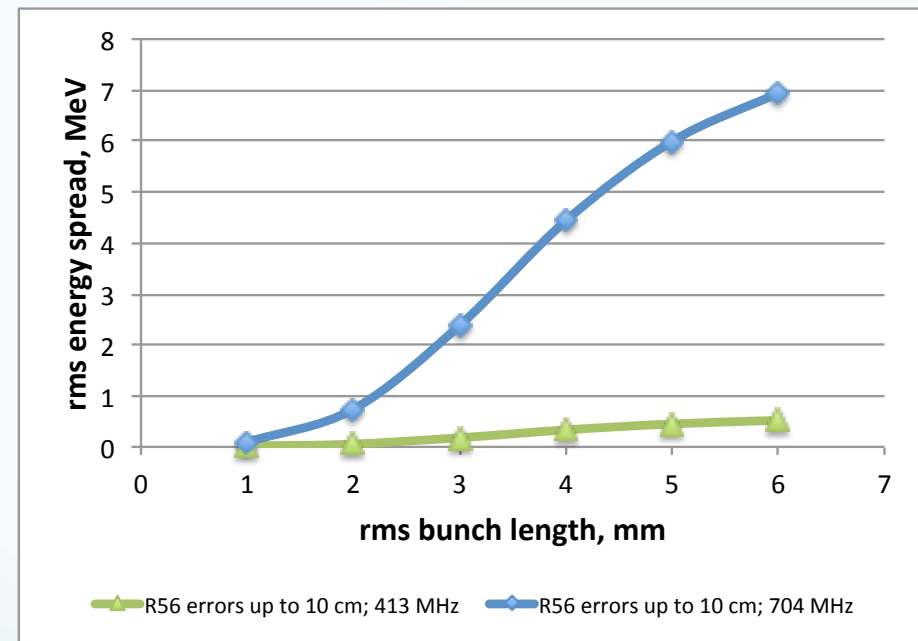The agreement within 1% with the simulation results.

Energy spread at 12 MeV due to errors

Path length errors

Legend:
- DL errors up to 1 mm; 413 MHz
- DL errors up to 0.1 mm; 413 MHz
- DL errors up to 1 mm; 704 MHz

Results are shown as average over 10 random seeds of ΔL errors (individual for each beam energy)

R_{56} errors

Legend:
- R56 errors up to 10 cm; 413 MHz
- R56 errors up to 10 cm; 704 MHz

Using 10 random seeds of R56 errors (individual for each beam energy)

Spin transparency of eRHIC arc

SLC problem: the betatron motion in the arcs was in the resonance with the spin motion. Thus the polarization was sensitive to the vertical orbits
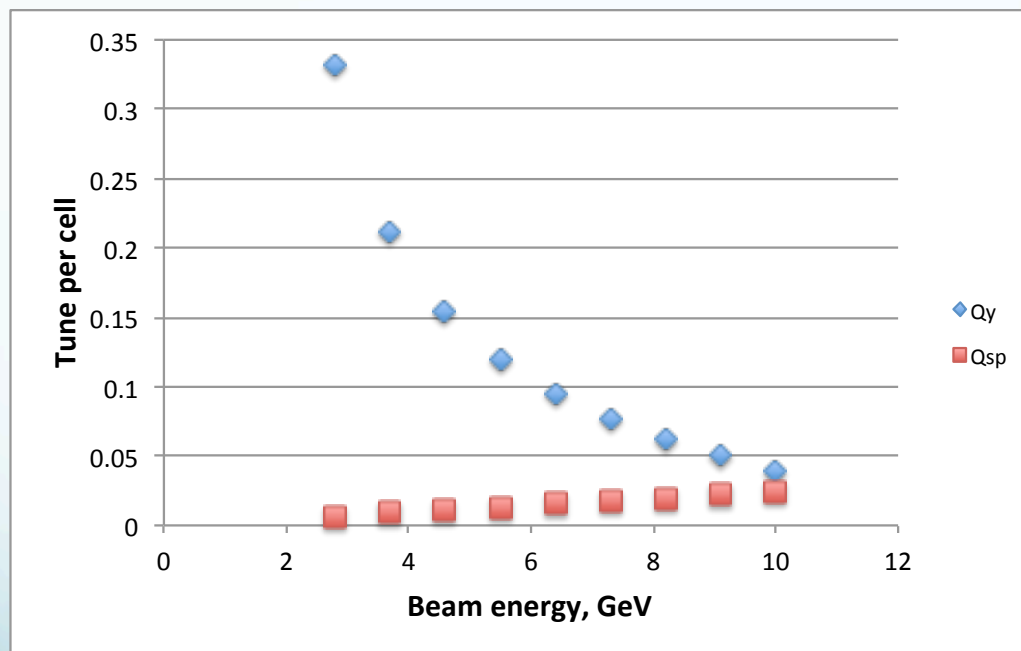
The check for the eRHIC cell that the betatron (vertical) and spin phase advances per cell are separated enough in all recirculating passes.

The vertical betatron and spin tunes are well separated.
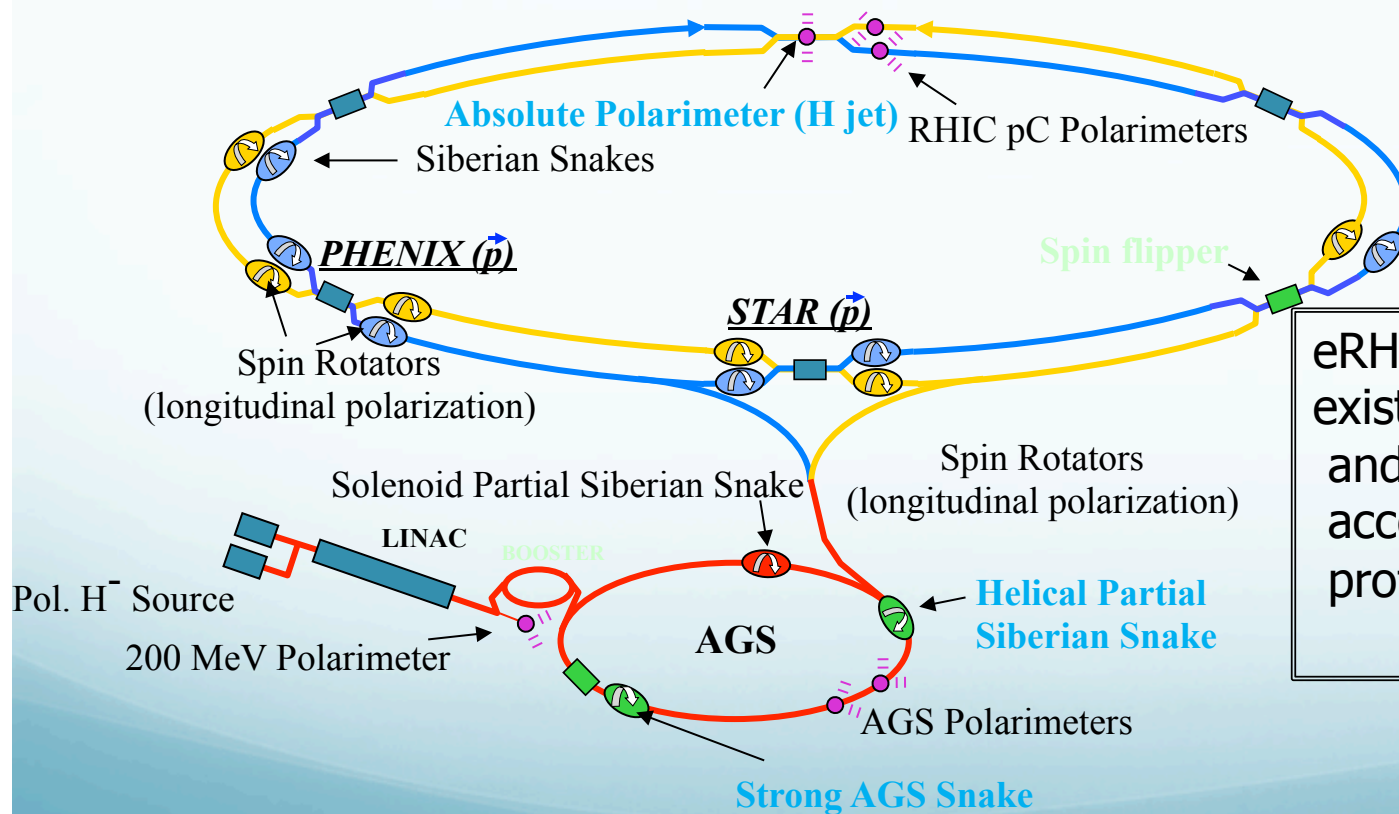More detailed results were obtained in simulations (F.Meot).

Summary

- The present design aims at ~10^{33} cm^{-2}s^{-1} luminosity, but contains a pathway to the future luminosity upgrades.

- The synchronization scheme accommodates a 16cm hadron delay line and the harmonic switching

- The acceptable longitudinal polarization level can be achieved without spin rotators, with small polarization loss due to the spin decoherence caused by the energy spread.

Backup slides

eRHIC: polarized protons

RHIC :
- only polarized proton collider in the world

-very successful Run-13: fully completed physics program at 255 GeV

-achieved beam polarization at 255 GeV 57-58% (H-jet polarimeter)

Absolute Polarimeter (H jet)   RHIC pC Polarimeters

Siberian Snakes

PHENIX (p̄)

Spin flipper

Spin Rotators
(longitudinal polarization)

STAR (p̄)

Solenoid Partial Siberian Snake

Spin Rotators
(longitudinal polarization)

LINAC

BOOSTER

Pol. H⁻ Source

200 MeV Polarimeter

AGS

Helical Partial
Siberian Snake

AGS Polarimeters

Strong AGS Snake

eRHIC will take favor of existing hardware in RHIC and in the injector chain to accelerate polarized protons up to 255 GeV.
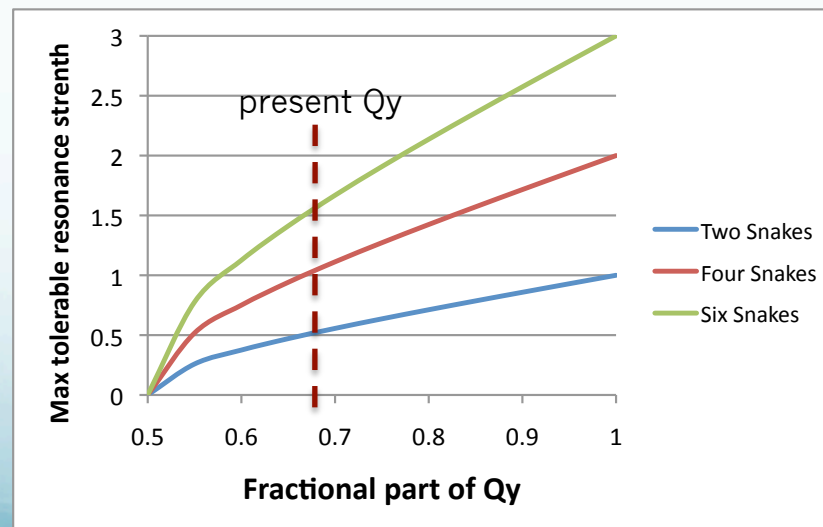
Towards higher proton polarization for eRHIC

A pathway to 70% proton polarization :

- Using smaller beam transverse emittances.

 *Beam scraping in Booster taking advantage of upgraded intensity of the polarized source.*

- Higher polarization from the source (85% or more)
- Increased number of Siberian Snakes (to 6 per ring)

Field of helical magnets required for longitudinal polarization in eRHIC

Red squares – eRHIC
Blue diamonds · RHIC
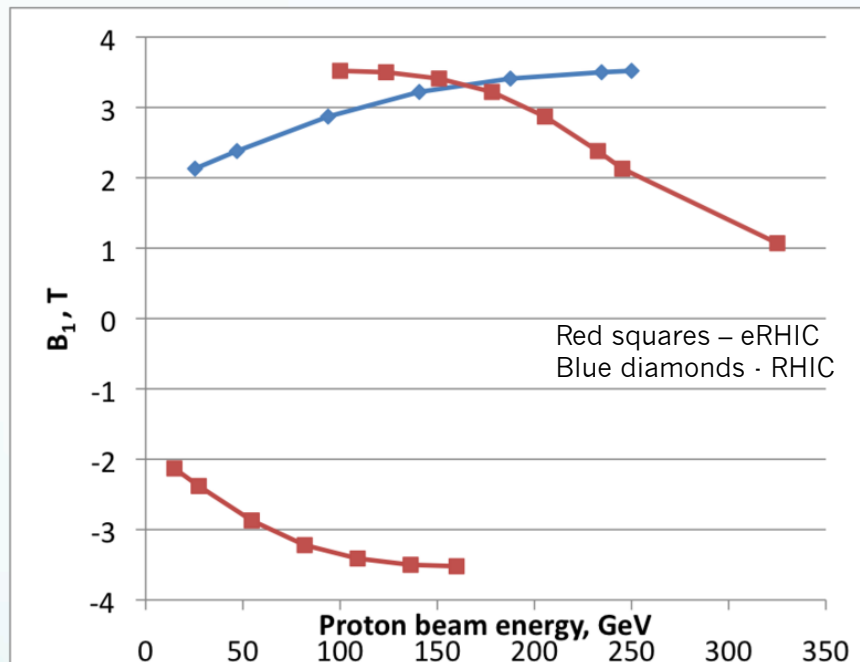
The magnet field of outer magnets, required for the longitudinal polarization in the IP, versus the beam energy].

Red squares – eRHIC
Blue diamonds · RHIC
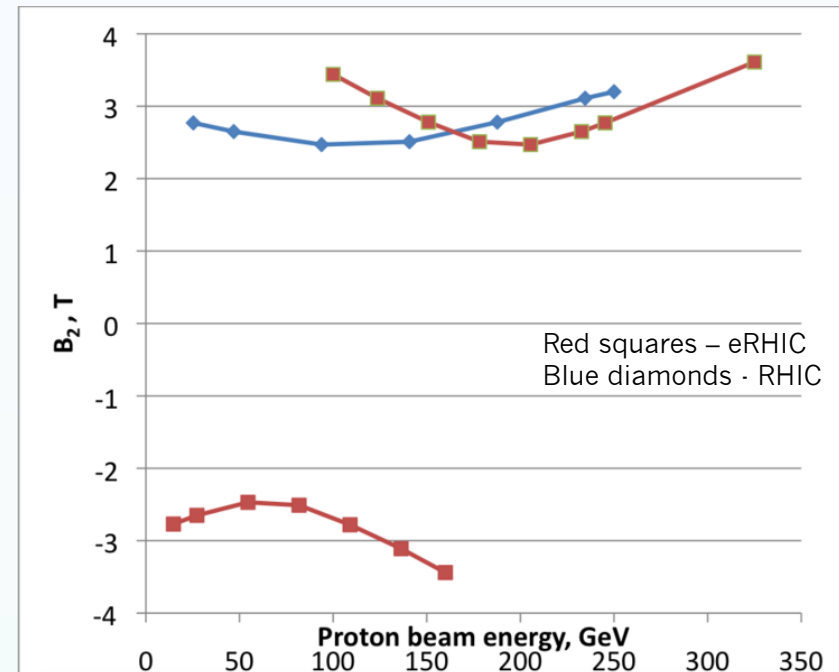
The magnet field of inner magnets, required for the longitudinal polarization in the IP, versus the beam energy.

The maximum required field ~3.6 T. In order to operate with the longitudinal polarization below 100 GeV proton energy the sign of the magnet field in all rotator magnets has to be switched.

Polarized $^3He^{+2}$ for eRHIC

- Polarized ^{3}He Source development (J.Maxwell's talk on Thursday).

- RHIC Siberian snakes and spin rotators can be used for the spin control, with less orbit excursions than with protons.

- More spin resonances. Larger resonance strength.
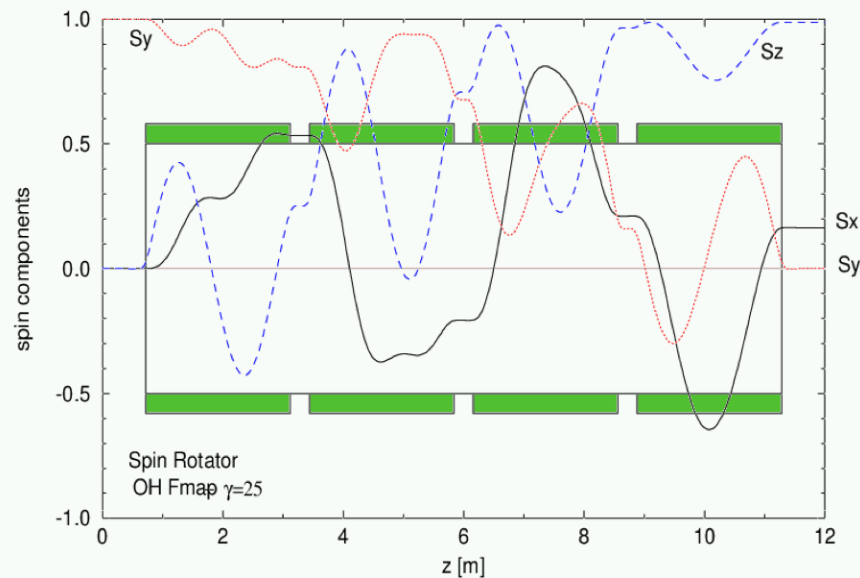
- Polarimetry.
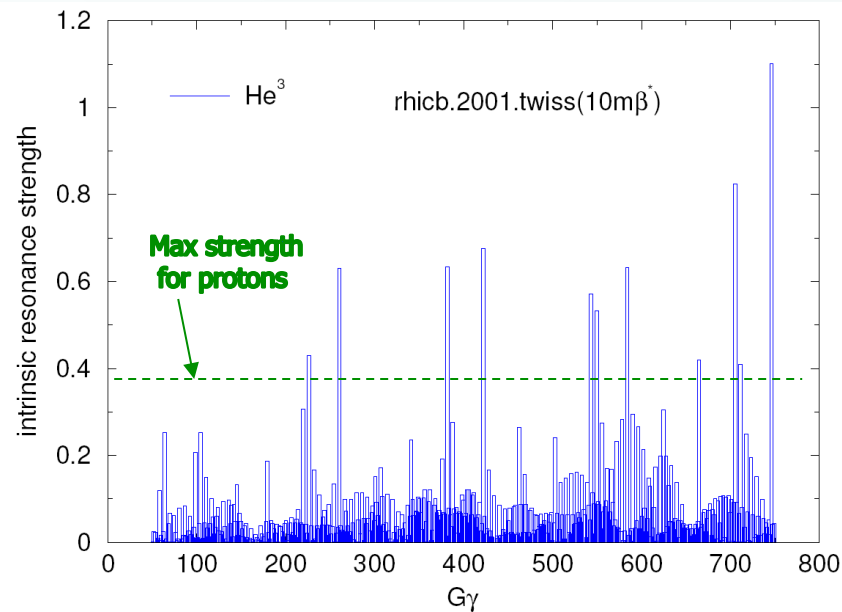
	$^3He^{+2}$	p
m, GeV	2.808	0.938
G	-4.18	1.79
E/n, GeV	16.2-166.7	24.3-250
γ	17.3-177	25.9-266
$\|G\gamma\|$	72.5-744.9	46.5-477.7

Present RHIC spin rotator

H1 +	H2 -	H2 +	H1 -
hor.	hor.	hor.	hor.
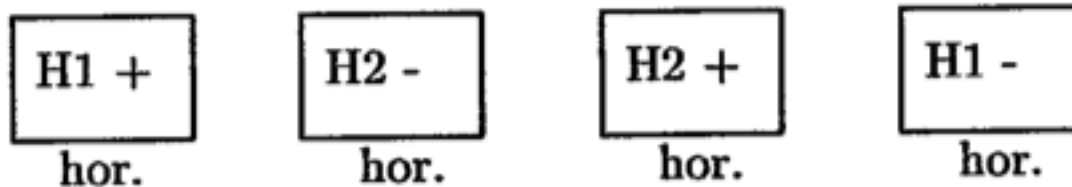
The spin rotator scheme, consisting of four helical magnet. The sign demonstrates the magnet helicity ("+" is right-handed, "-" is left-handed)
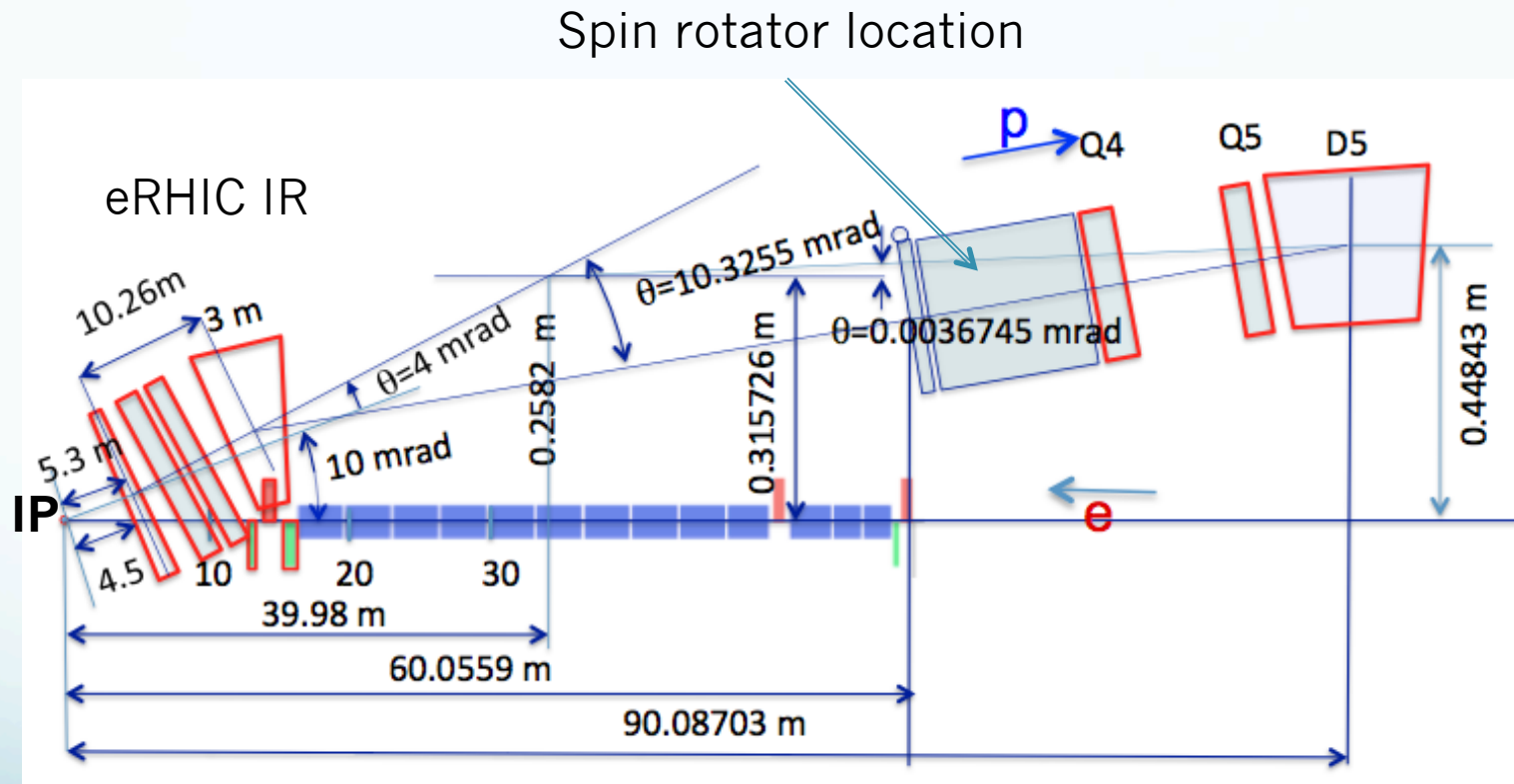
Can we use the same rotator in eRHIC?
- Saving money by reusing existing magnets
- Simpler switch between p-p and e-p operation modes, if needed

The example of the spin component evolution through the rotator. (Courtesy of W. MacKay)

Proton spin rotator location

Bending angle between the rotator and IP: 6.325 mrad

Possible techniques to reduce the spin decoherence

- Higher harmonic cavities to flatten the energy spread of the beam

- Siberian Snake(s) to change the sign of $\Delta\varphi_{sp}$ change rate

- Dispersion function slope at the interaction point

- Use lower frequency RF system in main linacs (to reduce induced energy spread)
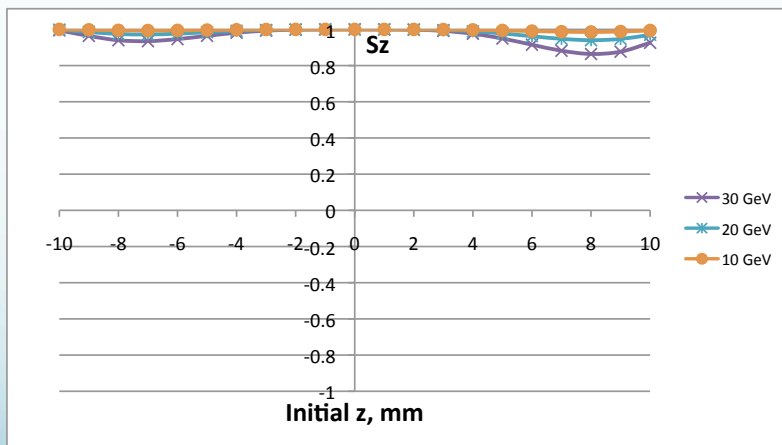
Lonigtudinal spin profile compensated by using 7th harmonic cavities
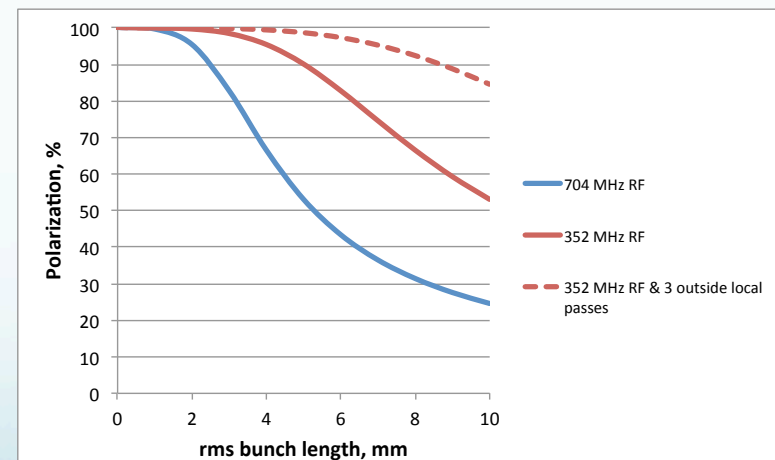
Polarization improvement due to lower frequency main RF system

luminosity of linac-ring collide

with round matched beams

$$L = \frac{1}{4\pi e} \frac{N_{h,p}}{\varepsilon_h} \frac{1}{\beta_h^*} I_e H_{hg} H_D$$

hadron beam brightness

hadron IP β function
- small *l**
- only one *hadron* beam
- new magnet technology Nb_3Sn

average e⁻ current boosted by energy recovery!

geometric overlap factor
- head-on collision
- small *e⁻* emittance

pinch enhancement
(1.3 for e⁻, 0.3 e⁺)

→ **ERL-ring collider**

Harmonic relations

	RF harmonic	Bunch harmonic	RF to bunch harmonic
Hadrons:	$f_{rf\_h} = h_h\, f_{rev\_h}$	$f_{b\_h} = n_h\, f_{rev\_h}$ $n_p = 120$	$f_{rf\_h} = m_h\, f_{b\_h}$
Electrons:	$f_{rf\_e} = h_e\, f_{rev\_e}$ $h_e \sim 5260\text{-}5300$	$\boxed{f_{b\_e} = f_{b\_h}}$ $\cancel{f_{b\_e} = n_e\, f_{rev\_e}}$	$f_{rf\_e} = m_e\, f_{b\_h}$ $m_e = 44$

Depends on the design circumference length
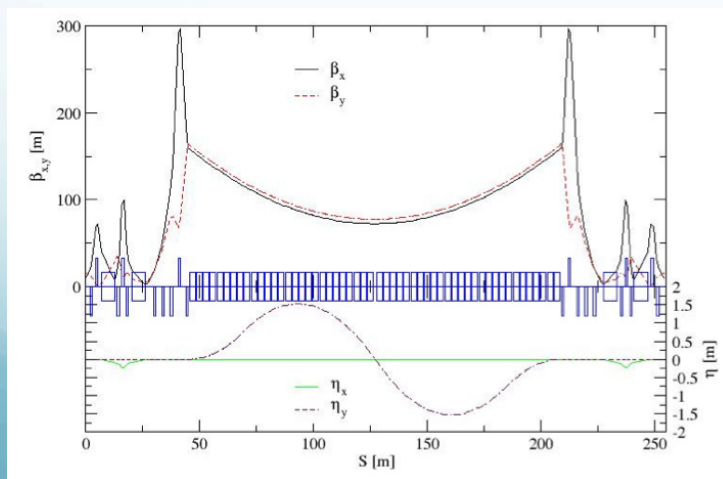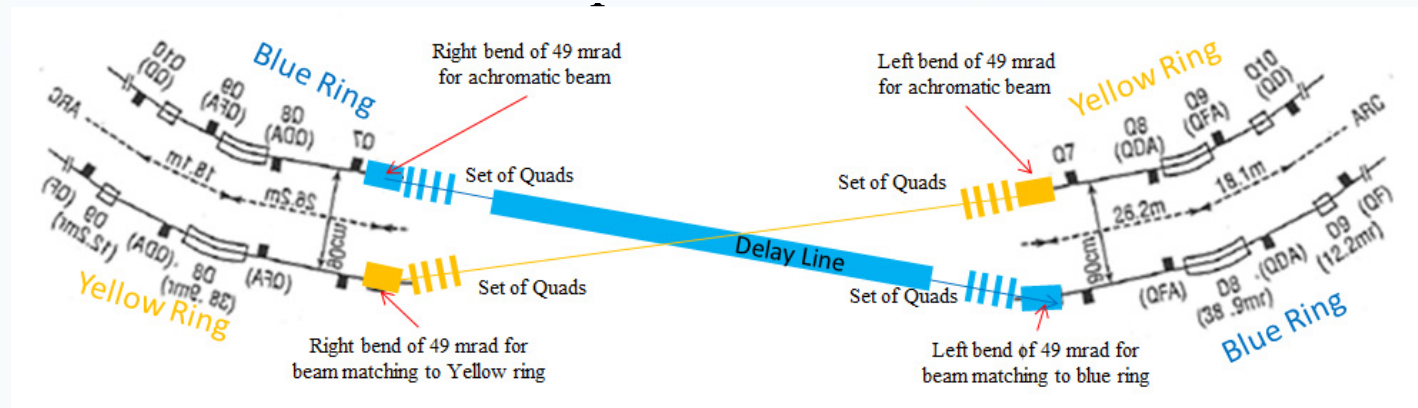
This condition is not required for recirculating linacs !

Collision synchronization

From this: $f_{rev\_e} = \dfrac{m_e n_h}{h_e} f_{rev\_h} = \dfrac{5280}{h_e} f_{rev\_h}$ $\Longrightarrow$ $C_e = \dfrac{h_e}{5280} \dfrac{C_h}{\beta_h}$

Ion Delay Line for RHIC

N.Tsoupas, et al., TUPFI079, IPAC'13

Up to 15 cm path length variation

It can be used for RHIC operation with asymmetric species, as well as for electron-hadron operation of future eRHIC.